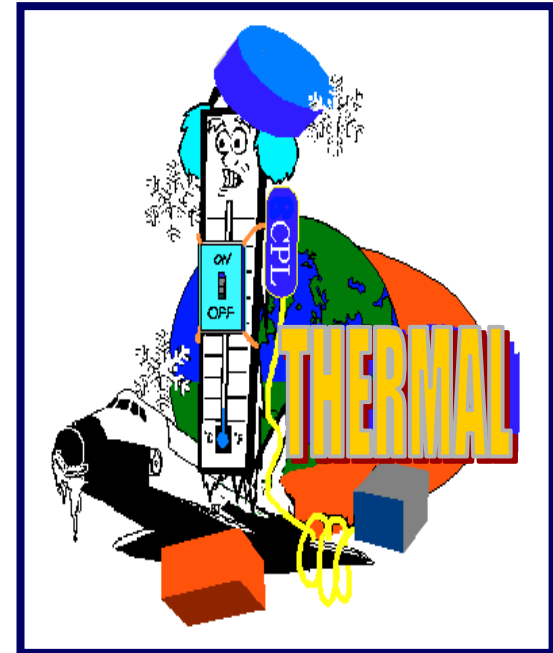## Dan Butler

Associate Branch Head
Thermal Engineering Branch, Code 545
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301-286-8618 (Office)
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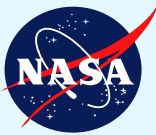charles.d.butler@nasa.gov

Presentation Prepared By:

## Wanda C. Peters

Thermal Coatings Group Manager
Swales Aerospace, Incorporated
301-286-5147 (Office)
wanda.c.peters@gsfc.nasa.gov

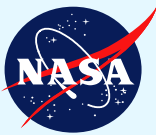NASA-GSFC Thermal Engineering Branch's Website Address
http://mscweb.gsfc.nasa.gov/545web/
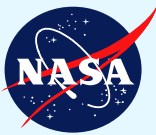
# Thermal Coatings Seminar

- What Are Thermal Control Systems?
- Selecting Thermal Control Coatings
- Types of Thermal Control Coatings
- Aerospace Thermal Coatings Vendors
- GSFC Thermal Coatings Endeavors
- Developmental Coatings Technologies
- Thermal Coatings Application
- GSFC Coatings Application Facilities
- Thermal Radiative Properties
- Thermal Property Measurements
- Factors That Influence Thermal Radiative Properties
- GSFC Coatings Measurement Instrumentation
- Space Environmental Effects
- GSFC Coatings Space Environmental Testing Facilities
- GSFC - Swales Thermal Coatings Team Members
- Thermal Coatings Team Function & Responsibilities
- GSFC Thermal Coatings Committee
- Concluding Comments
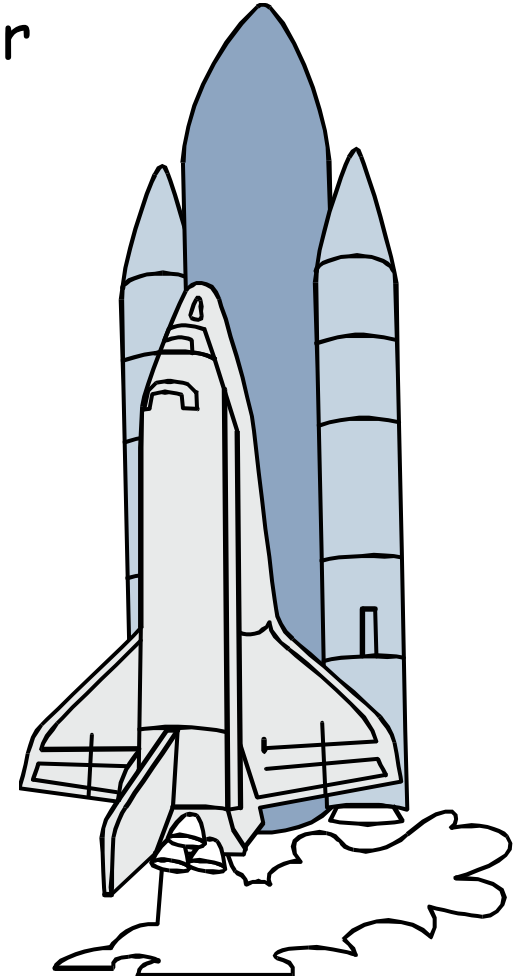
# What Are Thermal Control Systems?

- Thermal control systems are materials and/or devices which are utilized to control and maintain operating temperature requirements

- Thermal control systems are designed to be active or passive

  - Active controls require the utilization of variable emittance devices, loop heat pipes, heaters and/or louvers to maintain temperature control

  - Passive controls require the utilization of materials that reflect and absorb solar energy and radiate energy (heat) to space to maintain temperature control

- The space environment influences the selection of thermal control systems

  - The instability of materials and devices resulting from exposure to the space environment can cause failure of operating systems

- Therefore, space systems must be designed to operate within specified temperature limits and space environments over the lifetime of the mission
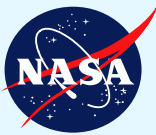
# Selecting a Thermal Control Coating

- Information to consider when making a selection:
  - Mission Parameters
  - Spacecraft Configuration
  - Desired Thermal Coating's Properties
  - Coating Application
  - Space Environmental Effects
  - Contamination Issues

- The selected thermal control coating should have:
  - Desired Solar Absorptance/Emissivity ($\alpha_s/\varepsilon$) Ratio
  - Good Space Environmental Stability
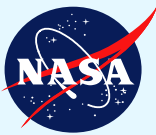  - Good Adhesion (if bonded or coated)
  - Handling Durability
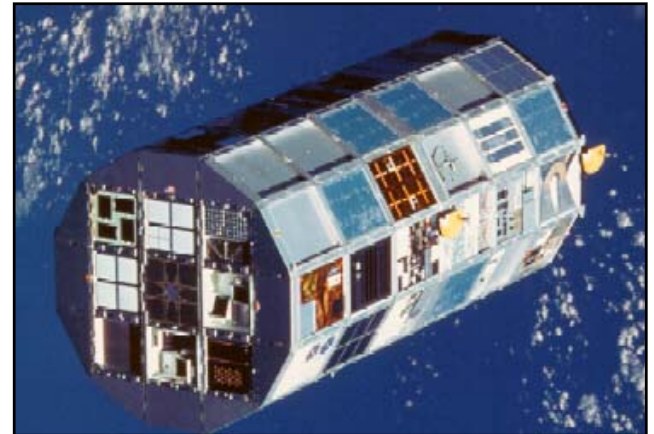


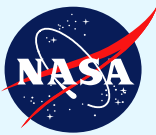*Thermal Control Surfaces Experiments on LDEF*

# Selecting A Thermal Control Coating

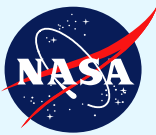| Desired Properties | Mission Parameters |
|---|---|
| ■ Thermal Radiative Property Range<br>  ● Wavelength Specifications<br>■ Diffuse or Specular<br>■ Survival Temperature Range/Limits<br>■ Opacity (vs. wavelength)<br>■ Coating Type<br>  ● Paint, Thin Film, Evaporated/Sputtered, Tape (w/adhesive specification), Anodized, etc.<br>■ Electrically Conductive or Non-Conductive<br>  ● What is the specific quantitative requirement?<br>■ Humidity requirements or susceptibility | ■ Orbit<br>  ● Including Planet and/or Moon<br>  ● Inclination<br>  ● Altitude<br>  ● Other pertinent orbit parameters<br>    ♦ Argument of Perigee, etc.<br>■ Mission Duration<br>  ● Mission Requirement<br>  ● Goal or Extended Mission<br>■ Spacecraft<br>  ● Attitude Control<br>  ● Orientation<br>    ♦ Sun, Inertially, Nadir<br>  ● Spinning versus Non-Spinning |

# Selecting A Thermal Control Coating

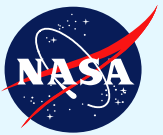| Coating Application | Spacecraft Configuration |
|---|---|
| ■ Substrate Information<br>    • Metal, Composite, Polymeric Film, etc.<br>    • Flexible Or Rigid Structure<br>    • Temperature Constraints<br>    • Cleaning Constraints<br>■ Coating and Substrate Material Compatibility<br>    • CTE Property Match or Mis-Match<br>    • Potential for Chemical or Electro-Chemical Interactions | ■ Coatings Locations<br>    • Internal versus External<br>    • Sun, Partial-Sun, No-Sun, Albedo, etc<br>    • Location relative to sensitive areas<br>        ♦ Optics, Lasers, Electronics, etc.<br>■ Radiator Location with respect to Vents Locations<br>■ Deployable Structure or Mechanism |

# Selecting A Thermal Control Coating

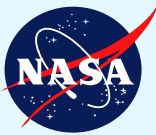| Space Environmental Effects | Contamination Issues (*Optional*) |
|---|---|
| <ul><li>Solar (UV) Exposure/Stability</li><ul><li>Direct</li><li>Albedo</li><li>Duration Of Exposure</li></ul><li>Atomic Oxygen Exposure/Stability</li><li>Radiation, Charged Particle Exposure/Stability</li><li>Thermal Cycling</li><ul><li>Specify Predicted Temperature Ranges</li><li>Number of Cycles</li></ul></ul> | <ul><li>Contamination Budget</li><ul><li>What is the contamination budget allocation for the specific coating, in terms of allowable</li><ul><li>Absorptance & Emittance Degradation</li><li>Molecular Contaminants Accretion</li><li>Particulate Contaminants Accretion</li><li>Percentage of Obscuration</li></ul></ul><li>Sensitive Locations</li><ul><li>Optics, Lasers, etc.</li></ul><li>Field Of View</li><ul><li>Outgassing/Molecular</li><li>Particles</li></ul><li>Cleaning</li><ul><li>Easily Cleaned</li><li>Difficult to Clean</li><li>Cannot be Cleaned</li></ul><li>Handling Requirements</li></ul> |

# Types of Thermal Controls Coatings

- **Paints** (Z93P, Z306, NS43C, MSA94B, NS43G, A276, Z307, Etc…)

- **Metals** (Al, Ag, Au, Ni, Stainless Steel, Cu, Mg, Ti, Etc….)

- **Thin Films** (Kapton®, Ge/Black Kapton®, Black Kapton®, CP-1, Mylar, Etc…)

- **Tapes** (Ag/FEP, Al/FEP, Al/Kapton®, Al Foil, Kapton®, Black Kapton®, Etc…)

- **Vacuum Deposited Coatings** [Evaporated/Sputtered]
  - **Metals** (Al, Ag, Au, Ti, Ge, Cr, Ni, Etc…)
  - **Dielectrics** ($Al_2O_3$, $SiO_x$, CCAg, CCAl, Dark Mirror, Etc…)

- **Conductive Coatings** (ITO, ATO, Ge, NS43C, NS43G, Z307, Etc…)

- **Anodized Aluminum** (Black, Hard, Clear, Gold, Plain, Etc…)

- **Chemical Conversion** (Irridite, Alodine, Etc.)

- **Optical Surface Reflectors** [OSR]

- **Solar Cells**

# Aerospace Thermal Coatings Vendors

- **Thin Films**
  - Dupont
  - Triton
  - SRS Technologies

- **Tapes**
  - Sheldahl
  - Dunmore
  - Dupont

- **OSR**
  - Pilkington
  - OCLI

- **Paints**
  - AZ Technology (AZTek)
  - Alion Science & Technology
  - Lord Chemical Products
  - Swales Aerospace
  - Ball Aerospace
  - Boeing

- **Evaporated/Sputtered Coatings**
  - Sheldahl
  - Dunmore
  - Astral Technology Unlimited (ATU)
  - OCLI

# Thermal Control Paints

- **White Paints**                                                             Vendors
    - Z93P or AZ93 (formerly Z93)          AZTechnology or Alion Science & Technology
    - S13GP:6N/LO-1 (formerly S13G/LO)     Alion Science & Technology
    - A276                                 Lord Chemical Products
    - NS43C (conductive)                   Swales Aerospace
    - NS43G (conductive off-white)         Swales Aerospace
    - AZW/LA-II                            AZTechnology
    - M1                                   Boeing (formerly Hughes Corporation)

- **Black Paints**
    - Z306                                 Lord Chermical Products
    - Z307 (conductive)                    Lord Chemical Products
    - MSA94B (conductive)                  Swales Aerospace
    - Ball IR Black                        Ball Aerospace
    - Nextel Velvet Black 811-21           Mankiewicz Coatings LLC
    - ElectroDAG 213 (conductive)          Acheson Colloids Company

# Dielectrics over Metals

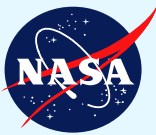| Composite Coatings[2, 3, 4] | Acronym | Material Stack | $\alpha$ | $\varepsilon(n)$ | $\varepsilon(h)$ | Surface Resistance |
|---|---|---|---|---|---|---|
| **Fixed Thermal Properties Composites** | | | | | | |
| ➤ Silver Composite[5] | CCAg | $SiO_x/Al_2O_3/Ag(Al_2O_3)$Substrate | .07 | .62 to .68 | .59 to .65 | TBD |
| ➤ Aluminum Composite | CCAl | $SiO_x/Al_2O_3/Al$/Substrate | .14 | .62 to .68 | .59 to .65 | $2.5\times10^9$ Ω/□ |
| **Tailored Emittance Composites*** | | | | | | |
| ➤ Aluminum Silicon Oxide | TEC-Al/SiO$_x$ | $SiO_x/Al$/Substrate | .14 | .03 to .62 | .04 to .54 | $1\times10^9$ Ω/□ |
| ➤ Aluminum Aluminum Oxide | TEC-Al/Al$_2$O$_3$ | $Al_2O_3/Al$/Substrate | .14 | .03 to .59 | .04 to .51 | *Not Measured* |
| ➤ Silver Aluminum Oxide[5] | TEC- Ag/Al$_2$O$_3$ | $Al_2O_3/Ag(Al_2O_3)$Substrate | .07 | .03 to .59 | .04 to .51 | *Not Measured* |
| ➤ Silver Silicon Oxide[5] | TEC-Ag/SiO$_x$ | $SiO_x/(Al_2O_3)Ag(Al_2O_3)$Substrate | .07 | .03 to .62 | .04 to .54 | *Not Measured* |

**NOTES:**

[1] **To Be Used As A Thin Film Coating Developmental Tool Only**. Contact Thermal Coating Committee for Official BOL Thermal Properties.

[2] The Coating Facilities for applying Composite Coatings with an $Al_2O_3$ layer have coating area limitations/size restrictions.
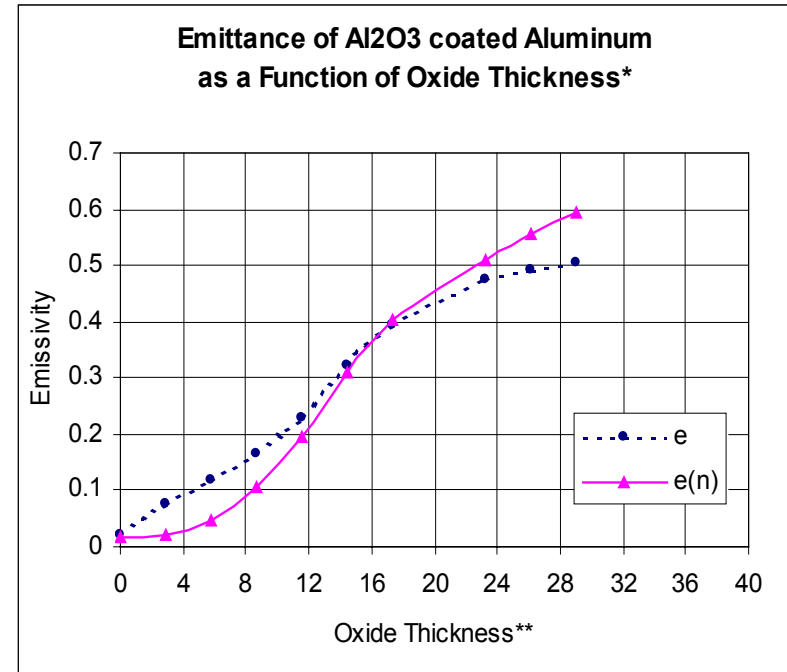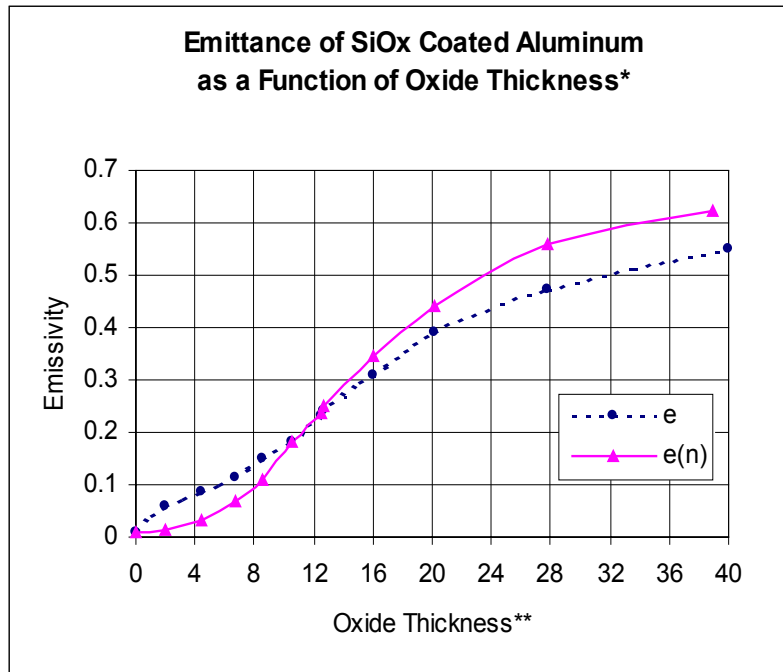
[3] Conductive Composite Coatings can be achieved by adding a top layer of ITO. The ITO will raise the $\alpha$ values of the coatings. The surface resistivity of the ITO coatings will vary as a function of relative humidity.

[4] Composite Coatings are typically highly specular, although the surface finish of the substrate may influence the specularity.

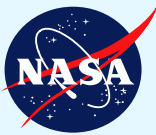[5] Aluminum Oxide ($Al_2O_3$) represented with parentheses denotes a binding layer that is needed when coating Ag.

# Dielectrics over Metals



**Emittance of SiOx Coated Aluminum as a Function of Oxide Thickness***

**Emittance of Al2O3 coated Aluminum as a Function of Oxide Thickness***

\* Charts reproduced from Heaney, Triolo, and Hass, "Evaporated Thin Films For Spacecraft Temperature Control Applications", July 1977.

\*\* Oxide Thickness is represented as $\lambda/4$ at 550 nm.
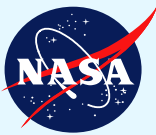
# GSFC Thermal Coatings Endeavors

- Astronaut Protective Sun Visor

  - GSFC supported Apollo and Skylab programs

  - GSFC is currently supporting JSC and the Shuttle program

  - The protective sun visor coating is a multi-layer evaporated thermal optical coating that is only produced at GSFC



Shuttle Extravehicular Visor Assemblies (SEVA)

- Mars and Lunar Explorations

  - GSFC Coatings Group provided coatings recommendations and coated samples to JSC for the investigation of the effects of Martian dust on radiator performance

  - GSFC Coatings Group is a member of the JSC team that was selected by Code T for the development of Heat Rejection Systems for Lunar Exploration
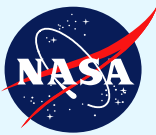


Z93P, NS43G, and 10-mil Ag/FEP Coupons

# Developmental Coatings Technology

*(Material Taken From ESLI SBIR Presentation by Dr. Timothy Knowles)*

- Lightweight Cryogenic Radiator (LCR)

  - NASA SBIR Phase II

  - IR Astronomy missions require passive cooling near 30 K

  - Black paints become transparent

  - ESLI VelBlack (carbon fiber velvet) is a good UV-VIS-NIR absorber

  - ESLI Carbon Microtruss is a good microwave absorber

  - Can be incorporated in the structure

- Energy Science Laboratories, Inc.
  - www.esli.com
  - Dr. Timothy Knowles, CEO
  - Christopher Seaman, LCR PI



VelBlack (2.5 mm thick) on Al foil

VelBlack Panel 0.6 m²

Carbon Microtruss @ 0.04 kg/m²
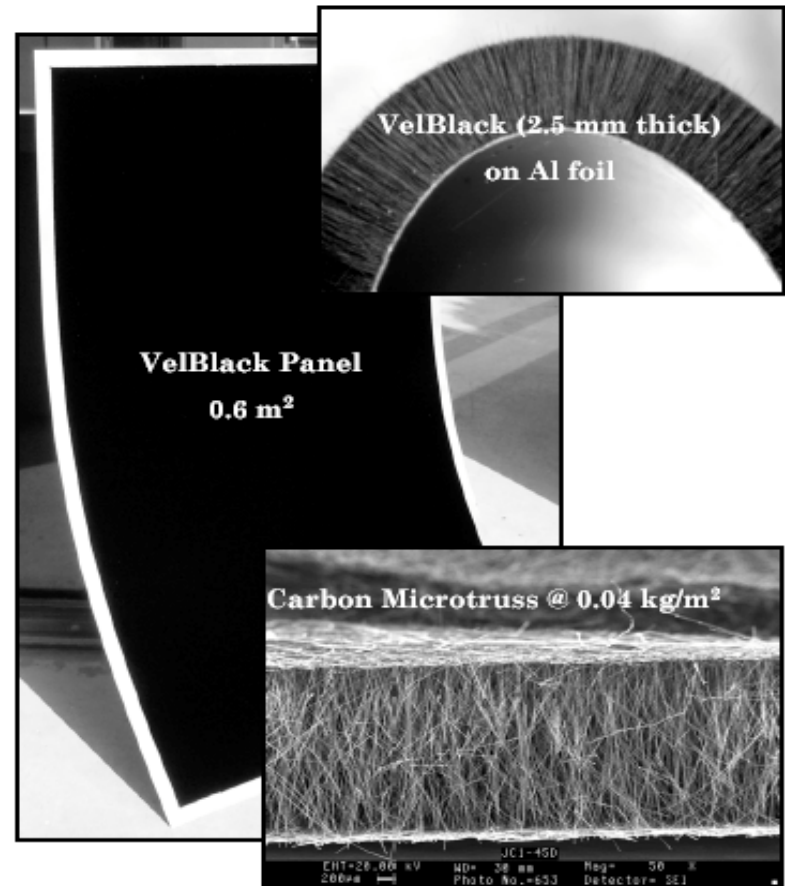
# Comparison of Black Thermal Coatings

*(Material Taken From ESLI SBIR Presentation by Dr. Timothy Knowles)*

Required minimum for JWST ISIM is 0.7@30K

- Lon Kauder, NASA-GSFC, calorimetric data
  - Error bars were removed for presentation clarity
  - Error bars are large at low T

- ESLI #2 has highest emittance at all temperatures
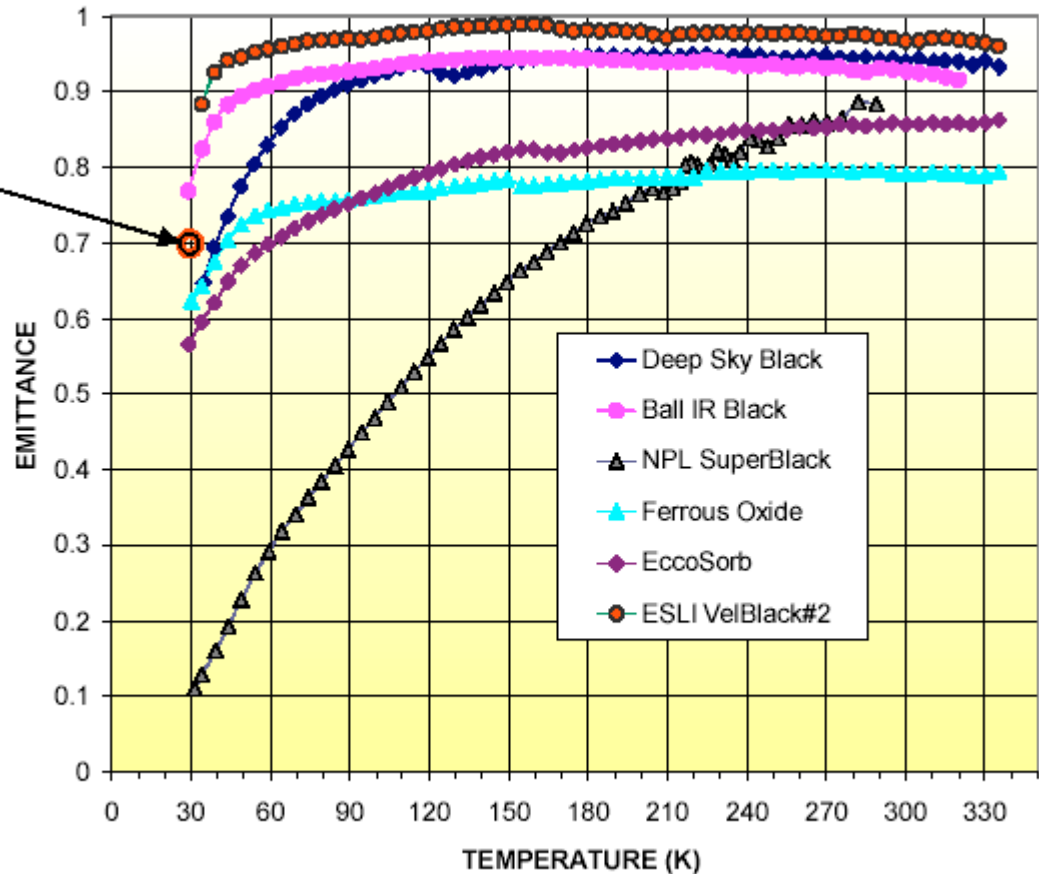


Legend:
- Deep Sky Black
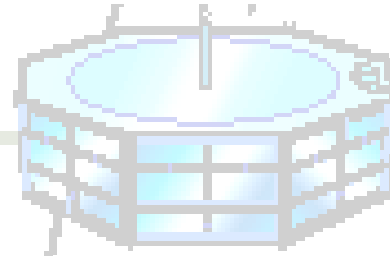- Ball IR Black
- NPL SuperBlack
- Ferrous Oxide
- EccoSorb
- ESLI VelBlack#2

X-axis: TEMPERATURE (K)
Y-axis: EMITTANCE

# New Millennium Program/Space Technology 5 (ST-5) Project



**Research-Quality Spacecraft**

**Micro-Satellite Design and Build**

**Constellation Mission**

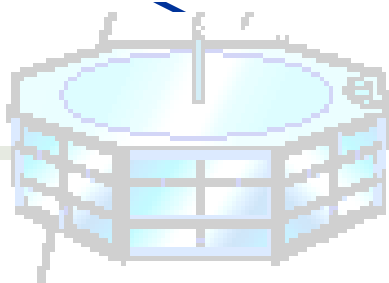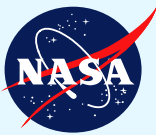**Technology Development Mission**
- Flight validation of new technologies
- Development and launch of three state-of-the-art small spacecraft
- Mass per nanosatellite $\leq$ 25 kg
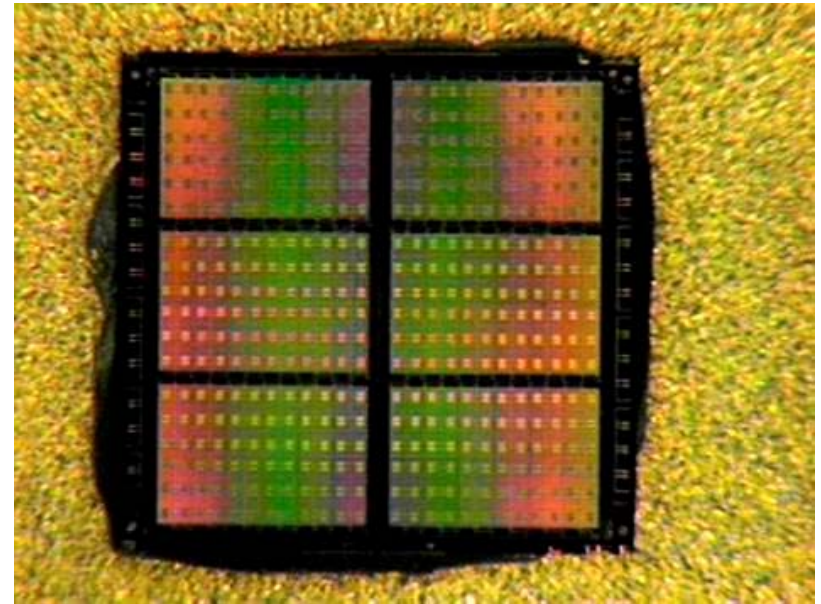- Short duration mission – 3 months
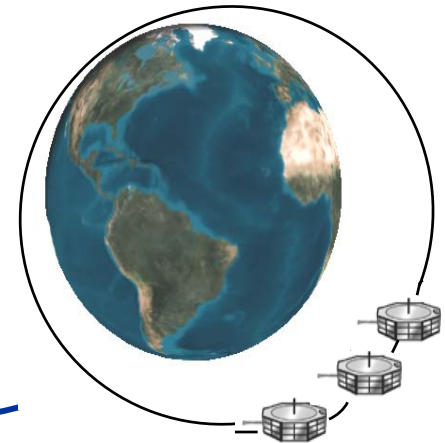
# ST-5 Project - Developmental Coatings Technology

*(Material Taken From Thermal Presentation by Donya Douglas)*

- Micro ElectroMechanical Systems (MEMS)
    - Arrays of micro-machined MEMS shutters, fabricated by Sandia National Laboratory
    - Effective emittance is modulated by varying the total number of arrays that are open
    - Shutter and Slits are 6 $\mu$m x 150 $\mu$m

- JHU Applied Physics Laboratory
    - Dr. Ann Darrin, MEMS Program Manager
    - Dr. Robert Osiander, MEMS PI
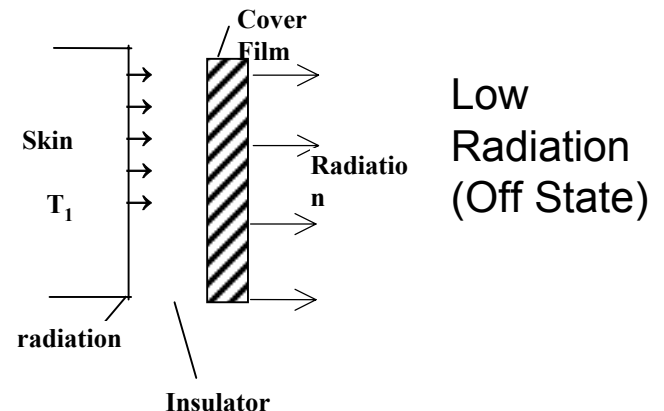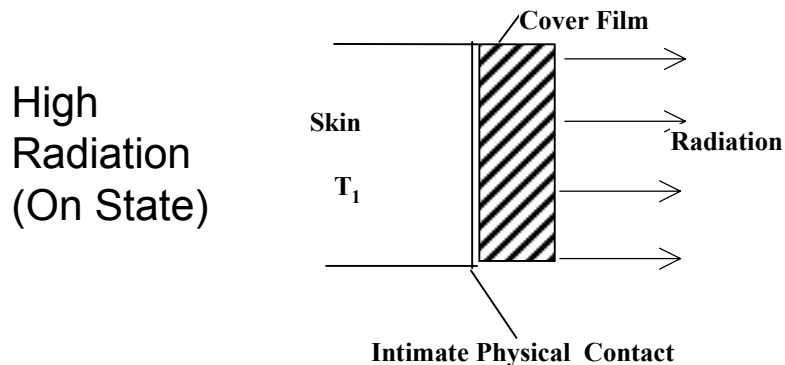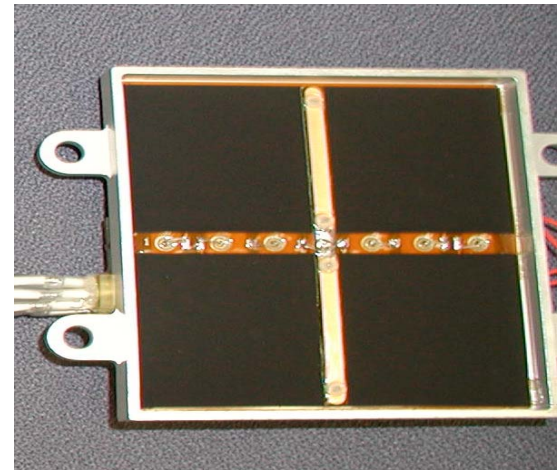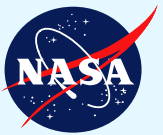    - Dawnielle Farrar, MEMS Instrument Manager

# ST-5 Project - Developmental Coatings Technology

*(Material Taken From Thermal Presentation by Donya Douglas)*

- ElectroStatic Flaps Radiator (ESR)
  - Simple approach to control radiation.
  - Changes between radiative or conductive heat transport via electrostatic forces
  - Thermal control film made of coated metalized polymer
  - Light weight and low power consumption

- Sensortex, Inc.
  - Dr. William Biter, Program Manager and PI
  - Steve Hess, ESR Instrument Manager

High Radiation (On State)

**Cover Film**

**Skin**

$T_1$

**Radiation**

**Intimate Physical Contact**

Low Radiation (Off State)

**Cover Film**

**Skin**

$T_1$

**Radiation**

**radiation**

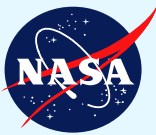**Insulator**

# Thermal Coating Application

- Thermal coatings applications typically consist of spraying, sputtering, evaporating, and taping

- The type of thermal coatings selected for application will depend on the substrate material and substrate properties:

  - Metal, graphite composite, thin film, polymer, etc

  - Flexible Or Rigid

  - Temperature constraints

  - Cleaning constraints

- Material compatibility between the thermal coatings and the substrate material will influence the coatings selection process

  - CTE properties match/mismatch

  - Chemical or Electro-Chemical interactions/reactions
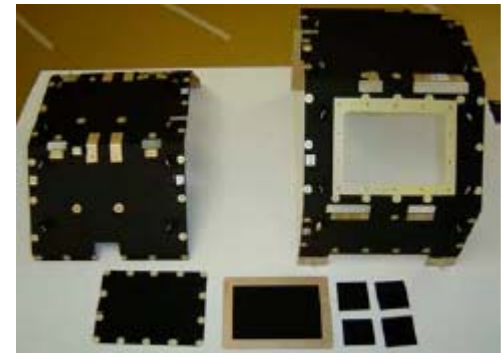


**ST-5 S/C Sidewalls**



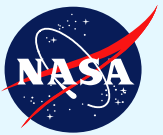**EOS AURA - TES Earth Shade VDA/Kapton/Composite/Honeycomb Panel**

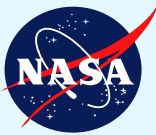# NASA-GSFC Thermal Control Coatings Application Facilities

- Large Spray Booth
- Small Spray Booth
- Convection Ovens
  - Large, Medium, & Small
- HVEC 72" Coater
- CVC Bell Jar Deposition System
- HVEC Bell Jar Deposition System
- Mill Lane SEVA Coating Facility
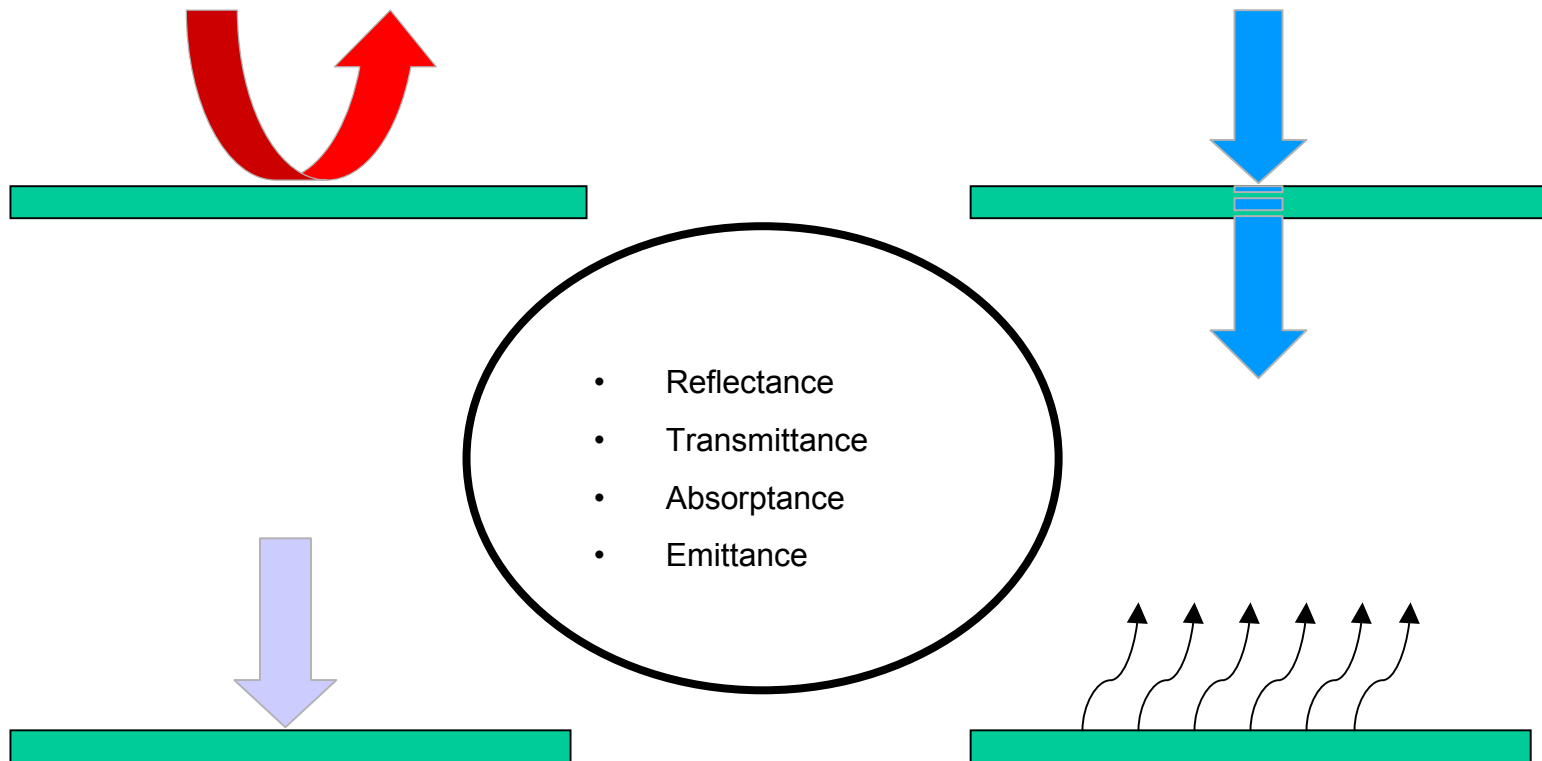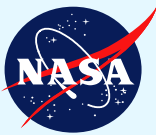- VEECO Bell Jar Deposition System

# Evaluation of Thermal Control Coatings

- To design a thermal control system that address the mission's requirements, the thermal radiative properties and durability of the material must be obtained through thermal optical/radiative property measurement and space environmental testing

- Thermal Optical/Radiative Properties (*Reflectance* = $\rho$, *Transmittance* = $\tau$, *Absorptance* = $\alpha$, *and Emittance* = $\varepsilon$) are used to evaluate a material's ability to maintain temperatures

- The reflectance of a material's surface is measured over the Infrared, Visible and Ultraviolet regions of the electromagnetic spectrum to calculate the solar absorptance and over the infrared region to calculate emittance

- Thermal coatings are tested for good coating adherence to the substrate through ASTM D-3359-97 Coating Adhesion testing and/or thermal cycle testing
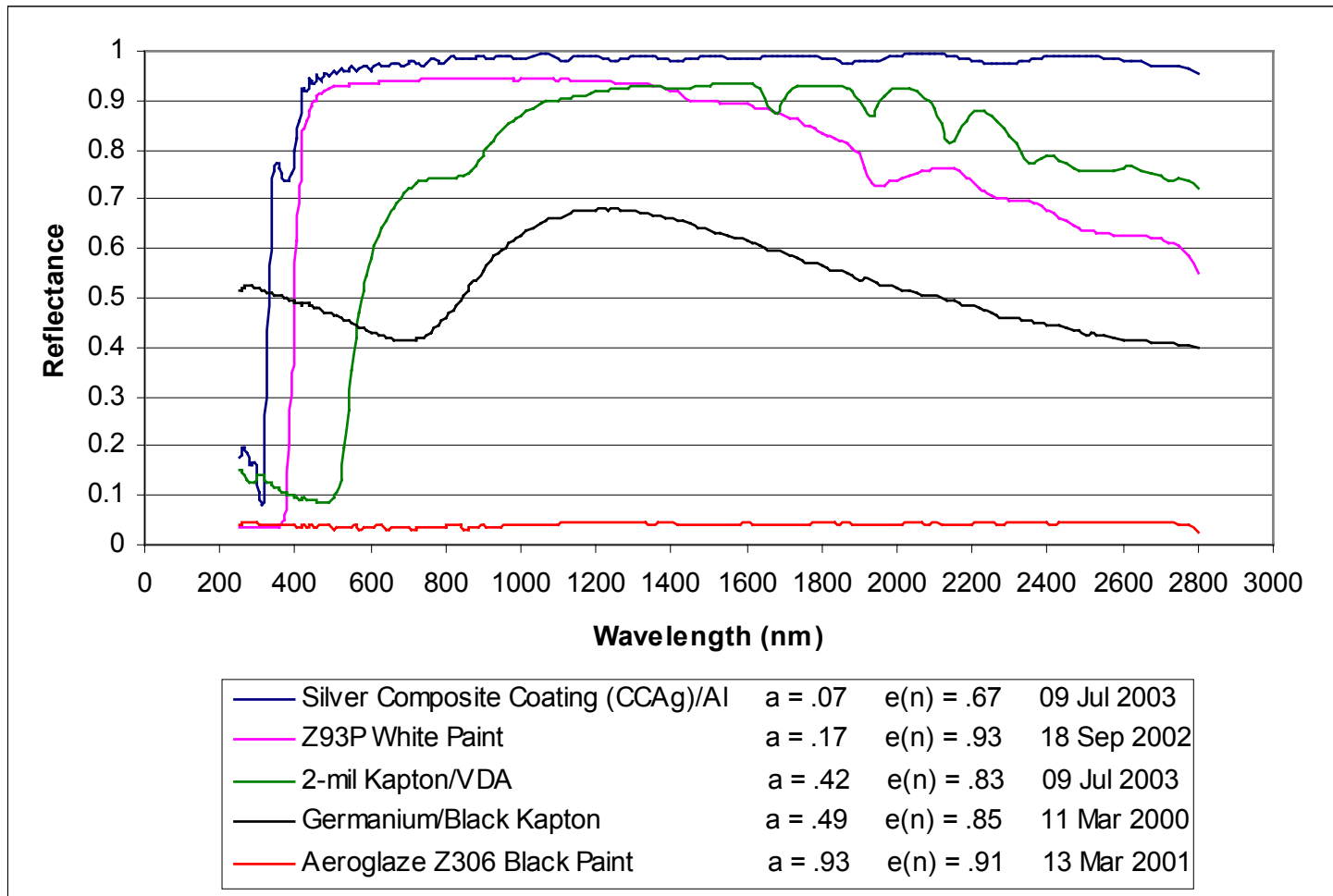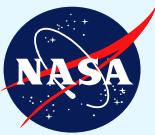
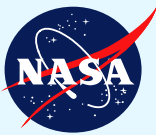# Thermal Radiative Properties of Coatings

- Reflectance
- Transmittance
- Absorptance
- Emittance

# Reflectance Curves of Various Thermal Coatings



| | | | |
|---|---|---|---|
| Silver Composite Coating (CCAg)/Al | a = .07 | e(n) = .67 | 09 Jul 2003 |
| Z93P White Paint | a = .17 | e(n) = .93 | 18 Sep 2002 |
| 2-mil Kapton/VDA | a = .42 | e(n) = .83 | 09 Jul 2003 |
| Germanium/Black Kapton | a = .49 | e(n) = .85 | 11 Mar 2000 |
| Aeroglaze Z306 Black Paint | a = .93 | e(n) = .91 | 13 Mar 2001 |

# Factors That Influence Thermal Radiative Properties

- Solar Absorptance and/or Emittance Values Influencing Factors:
  - Surface Finishes
    - Highly Polished (mirror-like/optical surface)
    - Polished
    - Buffed
    - Matt
    - Machined
  - Substrate Texture
    - Rough versus Smooth
    - Woven
    - Bead Blasted (sand, glass, etc…)
  - Immersion Rate for Chemical Coatings Processes (i.e., Anodized, Irridited)
  - Coating Thickness
  - Coating Adherence
  - Transmissivity
  - Electrical Conductivity
  - Contaminants
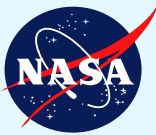  - Sample/Hardware Size and Configuration

# NASA-GSFC Thermal Control Coatings Measurement Instrumentation

- AZTek Laboratory Portable Spectroreflectometer (LPSR-300 and LPSR-200)

- Lambda 19 Near IR/Vis/UV Spectroreflectometer

- Geir-Dunkle DB-100 Reflectometer

- Bi-Directional Reflectance Distribution Function (BRDF)

- Nicolet FTIR Spectrometer

- OL750 Spectroradiometer
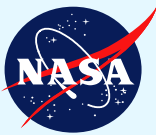
- Light Analyzer Microscopic Imager
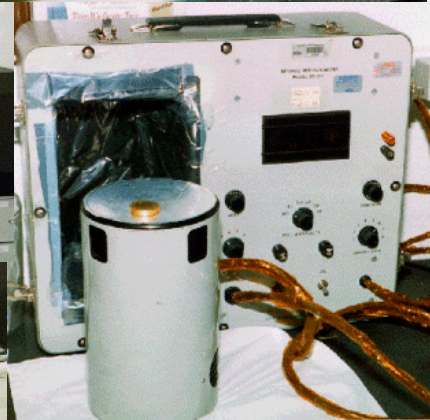
# Space Environmental Effects

- **Space environmental conditions considered in the selection of a coating:**

    - Solar Ultraviolet (UV) Exposure/Stability
        - Direct
        - Albedo
        - Duration of Exposure
    - Atomic Oxygen Exposure/Stability
        - Duration of exposure
    - Radiation, Charged Particle Exposure/Stability
    - Thermal Cycling
        - Specify Predicted Temperature Ranges
        - Number of Cycles

*MAP*
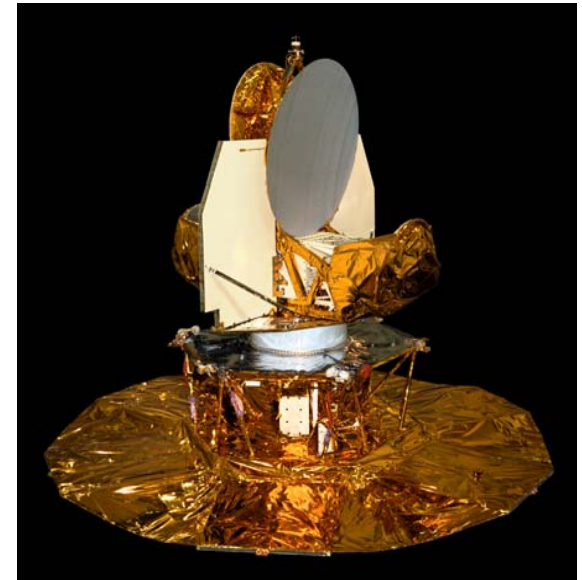
# Hubble and Space Environmental Effects

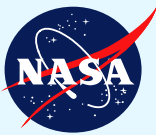*(Material provided by Jackie Townsend)*



**Hubble Space Telescope
Experienced Space Environmental Effects**

- The GSFC engineering team has an extensive hands-on experience in materials, coatings, contamination, and space environmental effects

    HST
    LDEF
    Solar Max

- Slow crack growth in polymers was experienced at levels below accepted normal damage thresholds

- Lesson learned from HST was that even when the environment is well defined, synergistic effects can still result in unforeseen degradation of materials
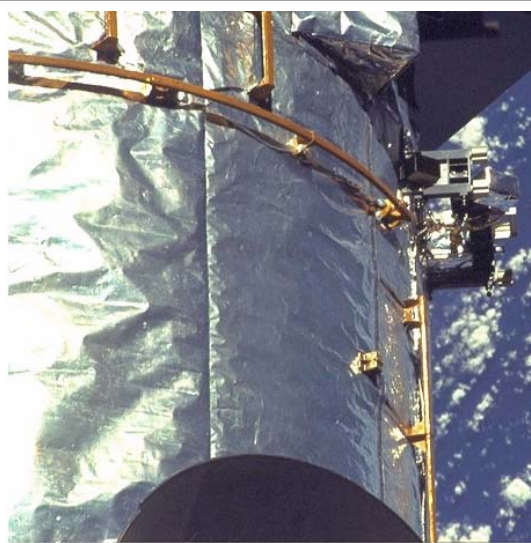
# Hubble's FEP Degradation Due to Space Environmental Effects

*(Material provided by Jackie Townsend.)*



HST SM1:  3.6 years in LEO



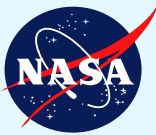HST SM2:  6.8 years in LEO



HST SM2:  6.8 years in LEO

- **HST at SM2 (6.8 years in LEO)**
  - 5-mil FEP Teflon with more than 100 cracks

- **Slow Crack Growth:** Synergistic effects of radiation (electron, proton, UV, VUV) and load (internal, blanket build and assembly, thermal cycling).  Evaluated temperatures accelerates degradation.
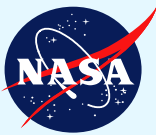
# Space Environment Effects

## Environment

- Thermal
    - Radiant thermal energy
    - Thermal cycling

- Ultraviolet

- Radiation
    - Trapped proton radiation belt particles
    - Trapped electron radiation belt particles
    - Solar wind radiation (low energy protons)

## Effects

- Thermal
    - Change in thermal radiative properties
    - Change in optical properties
    - Material degradation
    - Thermally induced jitters
    - Material fatigue
    - Reduced power system performance

- Ultraviolet
    - Change in solar absorptance
    - Change in optical properties
    - Material degradation

- Radiation
    - Material degradation
    - Change in thermal radiative property
    - Change in optical property
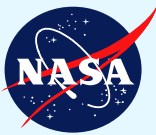    - Deep dielectric charging

# Space Environment Effects

## Environment

- Atomic Oxygen

- Contamination

- Plasma
  - Ionospheric plasma
  - Aurora plasma
  - Magnetospheric plasma (solar wind)

- Micrometeoroids and Orbital Debris
  - Meteoroid/orbital debris flux
  - Size, mass, velocity

## Effects

- Atomic oxygen
  - Surface erosion
  - Surface cleaning

- Contamination
  - Material degradation
  - Performance degradation

- Plasma
  - Arcing and surface charging
  - Re-attraction of contaminants
  - Change in thermal radiative property

- Micrometeoroids and orbital debris
  - Surface and structural damage
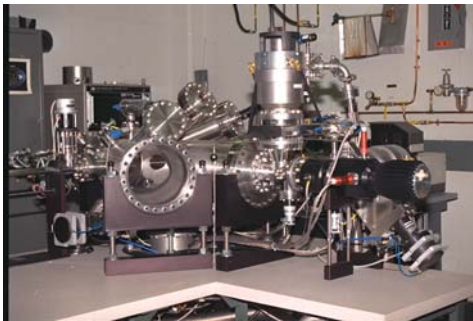  - Material degradation
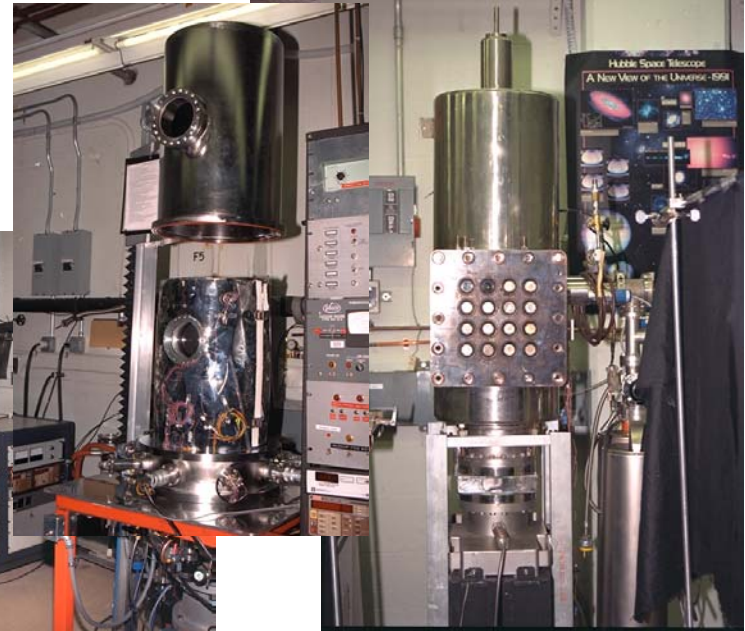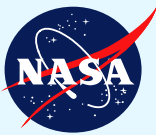
# NASA-GSFC Coatings Space Environmental Test Facilities

- Calorimetric Emittance Facility

- Multisedes "UV" Degradation Chamber

- Solar Wind Facility

- Electrostatic Charge Facility

- Thermal Cycling Chambers

- Various Vacuum Chambers

# The GSFC Thermal Coatings Team

**Goddard Space Flight Center**

SWALES AEROSPACE
*Contamination & Thermal Coatings*

- The GSFC thermal coatings team is comprised of NASA and Swales Aerospace employees

- The team provides technical expertise and support in the research, development, selection, application, BOL/EOL thermal radiative properties prediction, characterization, and flight readiness of thermal control coatings and materials to meet and exceed NASA mission requirements

# Thermal Coatings Team Members



## NASA/GSFC

- Lon Kauder ^ *
- Tom McCarthy *
- Ted Michalek *
- Jackie Townsend
- Eve Wooldridge+ *

## Swales Aerospace

- Joe Butterworth        - Wanda Peters ‡ *
- Robert Gorman          - Brian Rice
- George Harris          - Jack Triolo *
- C. Blake Miller        - Danielle Voce
- Grace Miller

*^ GSFC Thermal Coatings Committee Chairperson*
*+ GSFC Thermal Coatings Team Lead*
*‡ Swales Thermal Coatings Group Manager*
*\* GSFC Thermal Coatings Committee Members*

# Thermal Coatings Team Responsibilities and Functions

**Technical Consultation**
Assessment of Mission Needs
Selection of Coatings for Various Application
BOL/EOL Thermal Radiative Property Prediction
Specification of Application Requirements
Specification of Handling Requirements

**Research & Development**
Absorptance Tailoring of Coatings
Emittance Tailoring of Coatings
Application Techniques Improvements
Coatings for Gossamer Applications
Thermal Coatings & Composites

Thermal
Coatings
Team

**Coatings Application**
Thermal Control Paints
Thin Film Coatings
Visors' Protective Coating
Dielectric Coatings
Conductive Coatings
Lacquers
Tapes

**Coatings Flight Qualification**
Optical Property Characterization
Thermal Radiative Property Characterization
Hemispherical Emittance Characterization
Bi-Directional Reflectance Distribution Function
Light Scattering/Surface Specularity
Electrostatic Discharge Testing
UV Degradation Testing
Thermal Cycle Testing
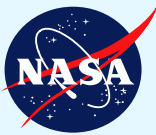Solar Wind Testing
Outgassing

# GSFC Thermal Coatings Committee

- Committee Chair:  Lon Kauder

- Members:  Tom McCarthy, Ted Michalek, Wanda Peters, Jack Triolo, and Eve Wooldridge

- The committee provides projects with the official NASA-GSFC Thermal Engineering Branch's BOL and EOL thermal radiative property predictions and thermal coatings selections per request of the thermal engineer

- Requests for BOL and/or EOL $\alpha$ and $\varepsilon$ values should include:  desired thermal property range, type of coating, coating application, substrate materials (if known), mission orbit, solar exposure, duration of mission (both specified and goal), and any contamination issues (if known)

- Requests should be made as early in the mission as possible to assist in mitigating potential problems in the selection of thermal coatings

- A meeting with the thermal engineer and the committee is required to fully address mission specifics

- BOL/EOL thermal property predictions are based on both flight and laboratory test data
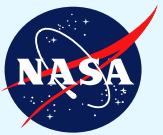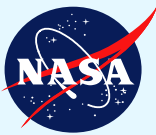
# Concluding Comments

- Thermal control coatings are an integral part of a space mission and are essential to the performance and survivability of the spacecraft and instruments

- Thermal radiative property measurement and space environmental testing are essential to the characterization of thermal control coatings, but ground testing has its limitations and cannot produce the synergistic effects seen in space

- Thermal integrity of coatings is very important and is one contributing factor to the success of a space mission

- Mechanical durability of thermal control coatings is also very important for the protection of spacecraft structures

- NASA/GSFC and Swales has a dedicated and experienced coatings team that addresses new and exciting thermal control coatings challenges

- The Coatings Team and Thermal Coatings Committee are available for thermal coatings consultation, application, measurement and testing upon request

# Back-Up Slides

# Thermal Radiative Properties

*(Information Obtained From Thermal Radiative Properties Coatings, <u>Thermaphysical Properties of Matter</u>, Volume 9)*
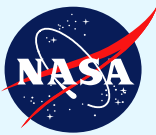
- Reflectance = $\rho$, Transmittance = $\tau$, and Absorptance = $\alpha$

- Radiant energy is reflected, transmitted and/or absorbed by a surface or material

$$\rho + \tau + \alpha = 1, \text{ for materials, where } \tau = 0, \rho + \alpha = 1$$

- Emittance ($\varepsilon$) is the rate at which a body radiates energy (heat) at a given temperature in relation to the rate a black body radiator radiates energy (heat) at the same temperature

- Kirchhoff's Law

  – Ideal black body is a surface that absorbs all of the radiant energy which strikes it, and appears black in color (provided its temperature is not so high that it is self-luminous). Any surface that absorbs all of the radiant energy is also the best emitting surface possible

  – Ideal radiator, when in thermal equilibrium, the body emits radiant energy at the same rate at which it absorbs
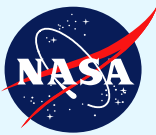
$$\alpha = \varepsilon$$
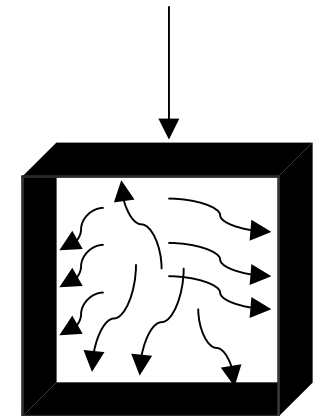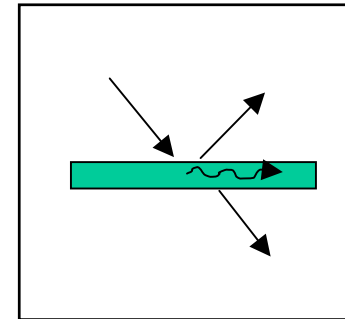
# Solar Absorptance Property Measurement

- At GSFC, the instrumentation used to calculate the solar absorptance measures over the spectral range of 250 to 2800 nanometers (.25 to 2.8 microns). An integrating sphere is used to measure the coating's reflectance for the solar absorptance calculation

- Solar Absorptance is the total solar energy absorbed by the surface divided by the total solar energy integrated as a function of the wavelength

$$\alpha_s = 1 - \frac{\int_{250}^{2800} R(\lambda) \cdot S(\lambda)\, d\lambda}{\int_{250}^{2800} S(\lambda)\, d\lambda}$$

- Where R = reflectance, S = solar energy, $\alpha_s$ = solar absorptance, and $\lambda$ = wavelength

- The reflectance measurement is performed near-normal (angle of incidence = 15°). This measurement is typically sufficient for most surfaces up to approximately 45°

- Whereas, when measuring cylindrical surfaces, spherical surfaces or angle of incidence greater than 45°, variations in the angle of incidence will influence the solar absorptance value and must be measured

- Typically the Johnson curve is used to represent the total solar energy over the solar spectrum
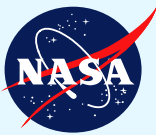
# Reflectance and the Johnson Curve
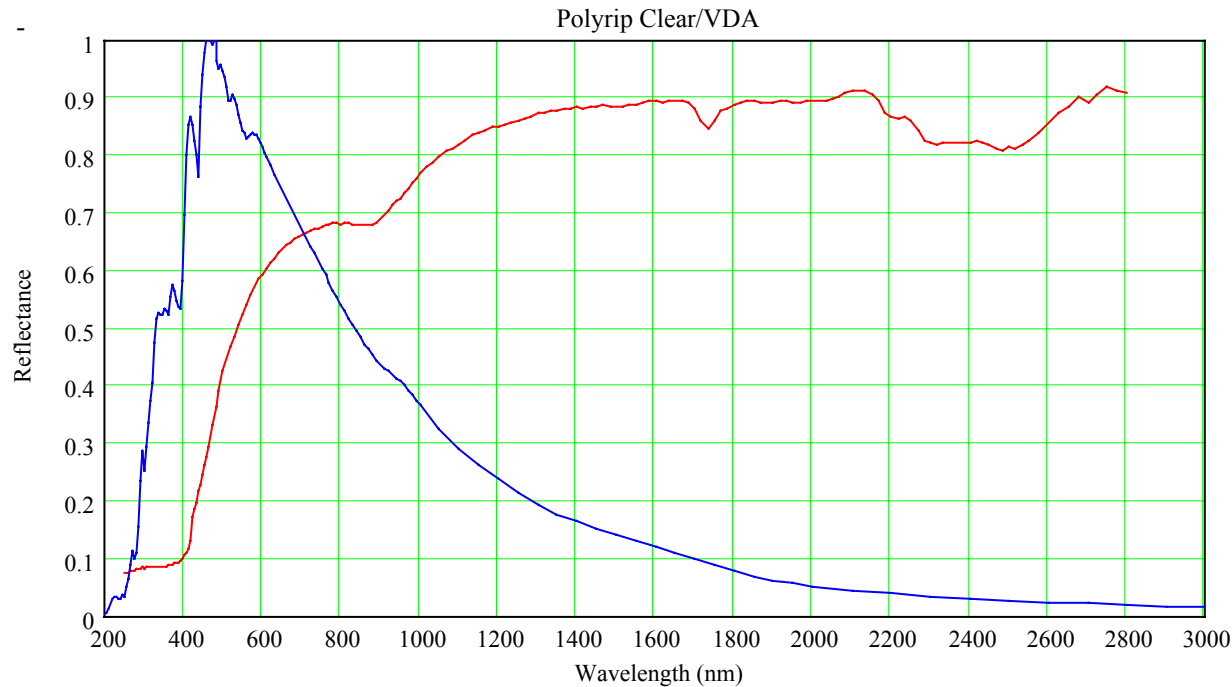


Polyrip Clear/VDA

Johnson curve (blue) and the Polyrip clear/VDA (red)
Solar Absorptance value = .405
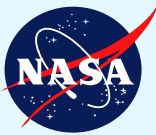
# Emittance Property Measurement

- Normal Emittance

  – At GSFC, the instrumentation used to calculate the normal emittance measures over the spectral range of 4 to 40 microns at room temperature

  – The normal emittance is calculated by measuring the reflectance of a material's surface in the infrared region of the spectrum and subtracting the measured reflectance from one (for opaque coatings only)

$$\varepsilon_n = 1 - \rho$$

- Hemispherical Emittance

  – For thermal modeling and analysis, the emittance must be in terms of a hemispherical (total body) emittance value.  Converting normal emittance to hemispherical emittance can be accomplished by using a conversion table and chart by E. Schmidt, E. Eckert, and M. Jakob

  – Hemispherical emittance can also be determined by calorimetric emittance measurement

  – With the addition of an ellipsoidal attachment, GSFC will also have the capability of calculating hemispherical emittance as a function of temperature by radiametric emittance measurement
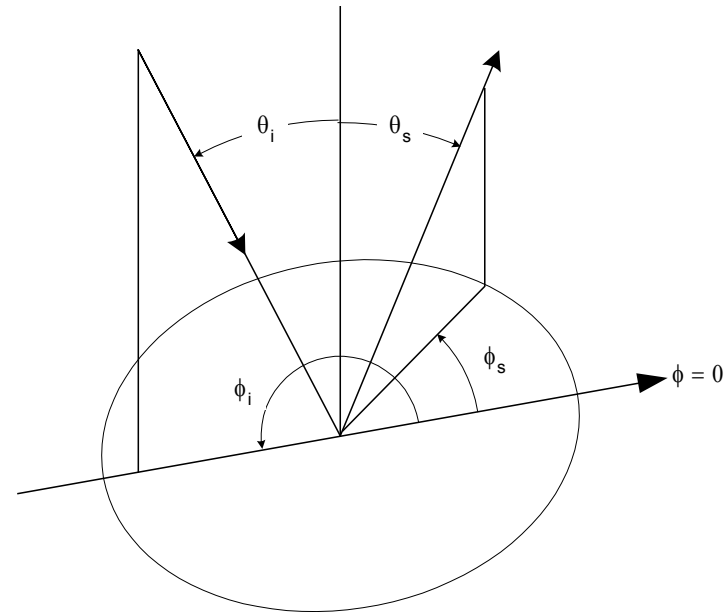
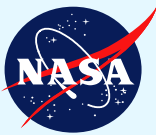# Bi-directional Reflectance Distribution Function

*(Material Taken Directly From a BRDF Presentation by Dr. Robert (Bob) Gorman.)*

- BRDF is a precise measurement of the intensity and direction of the reflection of light from a surface

$$\frac{\text{Power reflected per unit area per solid angle}}{\text{Power arriving per unit area} \; \mathbf{X} \; \cos(\theta_s)}$$

- BRDF is a point property of a surface. BRDF is a function of the direction of the incident light and the direction of the scattered light

- Our facility has the capability to measure light scattering at 632.8 nm, 442 nm, and 830 nm

# Bi-directional Reflectance Distribution Function

*(Material Taken Directly From a BRDF Presentation by Dr. Robert (Bob) Gorman.)*

- Perfectly diffuse or lambertian surface has constant BRDF;

    Power reflected per unit area per solid angle =
        BRDF  X  power arriving per unit area  X cos($\theta_s$)

- BRDF measurements/data are used to:
    – Calculate the amount of light or energy scattered by specific surfaces in critical applications
        • Example -- sunshield
    – Evaluate or monitor the condition of a surface with respect to contamination or roughness
        • Example -- optics (mirrors)
    – Determines specularity of surfaces for special cases
    – Calculate solar pressure